

NUMERICAL SIMULATIONS OF TRIGGERED STAR FORMATION. Harri Vanhala, Harvard-Smithsonian, Center for Astrophysics and University of Oulu, Finland, and A. G. W. Cameron, Harvard-Smithsonian, Center for Astrophysics.

The recently revived supernova trigger hypothesis [1,2] proposes that the formation of the solar system was initiated by an interstellar shock wave generated by a supernova explosion occurring a few parsecs away. In addition to triggering the collapse of the molecular cloud core, the shock wave also deposited fresh radioactivities into the precollapse core, giving rise to the anomalous abundances of extinct radionuclides measured in primitive meteorites. Conventional hydrodynamic simulations performed by Boss and Foster [3–5] have shown the mechanism to be capable of causing a molecular cloud core to collapse when the shock velocities are in the range of 10 to 25 km/s, at least when an isothermal equation of state and a marginally stable core are assumed. In the current work the shock mechanism is further examined by using the Smoothed Particle Hydrodynamics (SPH) method to investigate under what conditions the impact of an interstellar shock wave will cause a molecular cloud core to collapse.

The three-dimensional SPH code used in the calculations has been described in our report on the preliminary results [6]. The important details of the code include the employment of magnetic pseudo-fluid to include magnetic effects and the equation of state where the adiabatic index γ varies as a function of temperature and density. The total number of particles used in the simulation is in most cases between 30,000 and 40,000 particles. The cores are assumed to have evolved to their pre-impact state under the guidance of ambipolar diffusion, with the central density peak reaching values from 104 cm^{-3} to 107 cm^{-3} against the background density of 103 cm^{-3} . The shock velocities studied range from 10 to 50 km/s.

The current results suggest that the behavior of the system can in most cases be divided into three regimes according to the shock speed. At high speeds the momentum of the shock wave is so high that lower peak density cores are shredded apart. The exact velocity at which the shredding occurs is highly dependent on the initial density peak in the core; for lower density peaks ($\sim 10^4 \text{ cm}^{-3}$) it is $\sim 40 \text{ km/s}$ and it is higher for larger density peaks. At intermediate speeds ($\sim 25 \text{ km/s}$), the shock wave creates a bow shock, which compresses the facing side of the core and erodes the edges. The core is then stretched into a thin filament, the head of which may go into collapse and the tail of which flows in the post-shock stream (Fig. 1c). At low shock speeds ($\sim 10 \text{ km/s}$), the ram pressure of the shock front is insufficient to compress the core to collapse, and it rebounds from the maximum compression, the post-shock flow breaks it apart. These results are somewhat dependent on the initial density peak. If the density peak is so high ($> 10^7 \text{ cm}^{-3}$) that the pre-impact core is close to collapse, even low velocities may be sufficient to give the necessary final push. These highly evolved systems also withstand higher velocities without being shredded apart than do lower density cores.

The critical point in determining whether the shock is strong enough to compress the core is whether the principal coolants, CO and H_2 , survive in the shock front. At high shock velocities, these molecules are dissociated and the cooling times in the post-shock material are longer than the typical flow time past the core. At lower velocities, the molecules survive and cool the post-shock flow efficiently. The critical velocity for the destruction of the coolants is $\sim 19 \text{ km/s}$; below this value the shock is incapable of compressing the core to the point of collapse. For the intermediate velocities, the determining factor in whether the compressed core will collapse or bounce back is whether the temperature in the core material rises above a critical value of 25–30 K [2] and whether the magnetic pressure is too high to allow further compression.

Our calculations show no evidence of shock flow material being mixed into the core in the cases leading to collapse. At the shock velocities required to trigger collapse, the high temperatures of the shocked material create a high-entropy layer around the core, prohibiting inward mixing. Therefore, injection of radioactivities into the core is probably accomplished through a Kelvin-Helmholtz instability across the contact surface. The resolution of our calculations is inadequate to observe this effect.

The triggered collapse has two possible outcomes depending on the evolutionary stage of the pre-impact core. In well-evolved cores the central density peak is high and the radius small at the time of impact. In this case, the result is the collapse of a single mass concentration. If the core is weakly evolved, however, the maximum density in the core is smaller and the radius larger. Upon impact, the compressed core may fragment and form multiple centers of collapse. The exact criterion between the formation of a multiple system and the collapse to a single point depends on the details of the system, such as the shock velocity and the mass contained in the core.

Figure 1 shows a sequence of images from a simulation run leading to the formation of two collapsing fragments. The central density in the pre-impact core is $9 \times 10^4 \text{ cm}^{-3}$ and the shock velocity 25 km/s. The behavior of the system follows the general pattern for the intermediate shock speeds, from the creation of the bow shock (Fig. 1a) to the formation of the filament (Fig. 1c). The principal mass concentration forms at the head of the filament (denoted by large closed circles), and a secondary density peak (denoted by stars) is created downstream from it. The ram pressure from the post-shock flow accelerates the matter at the head of the filament to high velocities, causing the primary fragment to catch up with the secondary core (Fig. 1b) and eventually pass it (Fig. 1d). The wiggle in Fig. 1b is characteristic of all runs, and can be seen on larger scales as the roughly meandering pattern in the filament flow structure (Fig. 1c). At this point the simulation effectively terminates owing to the small time steps

caused by the rapid increase in density during the collapse, and it is unknown whether the fragments will remain separate (they are 750 AU apart) or merge later.

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References: [1] Cameron A. G. W. et al. (1995) *Ap. J. Lett.*, 447, L53–L57. [2] Cameron A. G. W. (1996) *LPS XXVII*, 191–192. [3] Boss A. P. (1995) *Ap. J.*, 439, 224–236. [4] Foster P. N. and Boss A. P. (1996) *LPS XXVII*, 377–378. [5] Foster P. N. and Boss A. P. (1996) *Ap. J.*, 468, 794. [6] Vanhala H. et al. (1996) *LPS XXVII*, 1357–1358.

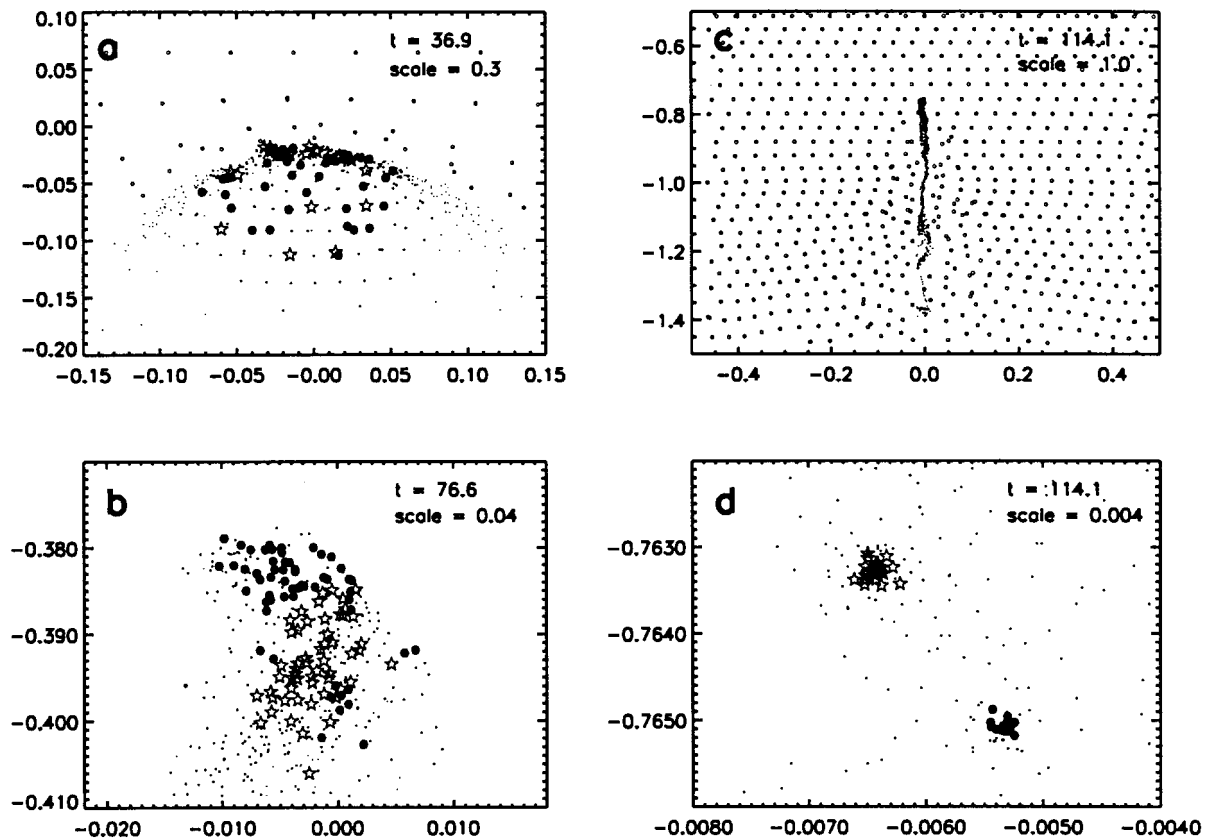


Fig. 1. Particle positions in a simulation run with 9,500 particles in the core and 11,500 in the shock flow. The shock flow material is denoted by small open circles, while the original molecular cloud core material is denoted by large filled symbols (particles that eventually form the primary core), stars (secondary core) or small dots (particles which end up being swept downstream). Each frame expresses the time since the beginning of the simulation run in 10^3 years and the scale of the image (relative to full size; Fig. 1c). The system is shown in the xz plane, with the units in parsecs. The initial shock velocity in the run is 25 km/s, resulting in a density jump of ~ 22 and a post-shock temperature of ~ 3700 K. The initial central density peak in the core is $9 \times 10^4 \text{ cm}^{-3}$ and the radius ~ 0.15 pc. The compressed central densities corresponding to the different frames are $2 \times 10^6 \text{ cm}^{-3}$ (Fig. 1a), $1 \times 10^8 \text{ cm}^{-3}$ (Fig. 1b) and $5 \times 10^{17} \text{ cm}^{-3}$ (Fig. 1c). Figures 1c and 1d are at the same instant in time, but at a different scale.